

HYDROGEN FOR DECARBONIZED ENERGY SYSTEMS: COMBUSTION CHARACTERISTICS, AND APPLICATIONS IN FURNACES, ENGINES, TURBINES, AND MICROGRIDS

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Hydrogen is becoming a key part of global plans to cut carbon emissions in power generation, transportation, industrial heat, and integrated microgrid systems. This paper examines the production pathways of hydrogen specifically grey, blue, green, pink, brown/black, and naturally occurring white hydrogen and assesses their techno-economic maturity in relation to projected demand trajectories through 2050. The combustion properties of hydrogen are analyzed comprehensively, highlighting its extensive flammability limits, elevated flame velocities, minimal ignition energy requirements, diffusive-thermal instabilities, and tendencies for NO_x formation. These characteristics have a big impact on how hydrogen-fired furnaces, spark-ignition (SI) and compression-ignition (CI) engines, and advanced gas turbine combustors are designed and used. In furnaces, using hydrogen-enriched and pure-H₂ operation can greatly lower CO₂ levels, but the burners need to be redesigned to stop flashback and NO_x. SI hydrogen engines are getting continue to improve, thanks to direct injection, Exhaust Gas Recirculation (EGR), boosting, and knock mitigation. Hydrogen-diesel dual-fuel CI systems, on the other hand, are very efficient and produce less carbon. Gas turbines have problems with flashback, thermoacoustic instabilities, and mixing non-uniformities. This has led OEMs to use multi-nozzle, cluster-type, and low-NO_x combustor architectures. The study also talks about how hydrogen is used in hybrid renewable microgrids, which use electrolysis, Combined Heat and Power (CHP) units, and thermal recovery to store energy for a long time. Collectively, the findings demonstrate hydrogen's strong potential to decarbonize multi-sector energy systems.

Keywords: hydrogen; decarbonization; furnaces; engines turbines

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1. Introduction

Hydrogen categories are characterized by their production methods and associated carbon emissions. Grey hydrogen is derived from steam-methane reforming of natural gas, resulting in significant CO₂ emissions. Blue hydrogen employs the same process but incorporates carbon capture and storage (CCS). Green hydrogen is generated through water electrolysis powered by renewable sources such as wind, solar, or hydro, yielding near-zero emissions at the production stage. Pink hydrogen utilizes nuclear energy for electrolysis. Black/Brown hydrogen is produced from coal or lignite, associated with very high emissions. White hydrogen pertains to naturally occurring subsurface hydrogen, currently under exploration but not yet extensively utilized.

Achieving net-zero greenhouse gas emissions by 2050 necessitates significant, sector-specific reductions that electrification alone cannot provide [1–2]. The United States emits more than 6,000 million tons of CO₂ annually, with approximate sectoral contributions of 1,500 Mt/yr from power, over 2,000 Mt/yr from transportation, 1,500 Mt/yr from industry, and more than 500 Mt/yr from buildings; aviation now accounts for 200 Mt/yr and may reach 400 Mt/yr by mid-century without intervention. In this setting, hydrogen serves as a systemic tool for decarbonization along with renewable energy [3–4].

In the United States, the demand for clean hydrogen is projected to be approximately 10 million metric tons per year by 2030, around 20 million metric tons per year by 2040, and about 50 million metric tons per year by 2050 [5].

Currently, the cost of hydrogen is roughly 1 dollar per kilogram for grey hydrogen, around 1.5 dollars per kilogram for blue hydrogen, and between 5 and 6 dollars per kilogram for green hydrogen produced using proton exchange membrane electrolysis using standard grid electricity. The expense of electrolysis is rapidly declining: with electricity priced at around 30 dollars per megawatt-hour, green hydrogen costs about 2 dollars per kilogram; with electricity under 20 dollars per megawatt-hour and mass-produced equipment, a fee of approximately 1 dollar per kilogram is attainable (United States Department of Energy “Hydrogen Shot”). Prominent solar power purchase agreements in highly sunlit areas are currently around 20 to 45 dollars per megawatt-hour, indicating costs below approximately 2 dollars per kilogram; high-capacity offshore wind may achieve approximately 1.5 to 2 dollars per kilogram over time, although its electricity typically incurs higher costs than the least expensive solar options. A net-zero trajectory necessitates about 700 gigawatts of electrolysis by 2030, although the current installed capacity has only recently exceeded 1 gigawatt; even when including stated projects, projections for 2030 range from approximately 50 to 240 gigawatts. [3–4, 6–8].

Pipelines are the most economical method for transporting hydrogen across local and regional distances. Europe intends to establish around 39,700 kilometers of hydrogen pipes by 2040, with around 69 percent constructed from existing gas infrastructure. Transporting liquid hydrogen is more challenging and expensive: it requires cooling to minus 253 degrees Celsius, experiences an approximate daily boil-off loss of 0.4 percent, consumes about 25 to 40 percent of its energy for liquefaction, and incurs costs of approximately 1.7 to 2.3 dollars per kilogram for long-distance journeys of around 10,000 kilometers [3,5]. Ammonia is generally the superior long-distance transport medium: it can be transported via the current global infrastructure of over 200 ports managing over 20 million tons annually, with ocean freight prices typically ranging from 40 to 60 dollars per ton of ammonia [3,5].

Ammonia can carry hydrogen and can also be burned as fuel, in a climate pathway that limits warming to 1.5 degrees Celsius. With learning and large plants, the cost to make hydrogen tends to be around 1 dollar per kilogram. Shipping ammonia over very long distances of about 20,000 kilometers is about 0.8 dollars per kilogram. If users burn ammonia directly and avoid converting it back to hydrogen, the delivery service can be about \$ 1.5 to \$ 2 per kilogram. About half of the traded volumes are expected to move by pipeline within regions and half by ship between areas, mainly as ammonia [5].

On land, hydrogen is aimed at jobs where batteries face limits in weight, space, or charging time. By 2030, scenarios allocate about 45 to 58 percent of hydrogen and hydrogen-based fuels to road transport. Today, heavy trucks with fuel cells still cost more to own and run than diesel by about 10 to 45 percent, but this gap is expected to fall by about one-half by 2050. Current compressed hydrogen tanks at 350 or 700 bar hold about 18 kilograms per cubic meter at 350 bar and about 27 kilograms per cubic meter at 700 bar. The European Union proposes one refueling station of at least 2 tons per day every 150 kilometers for 700-bar dispensing and one liquid-hydrogen station every 450 kilometers on main roads [3-4].

EU targets 20 million tons per year of domestic renewable hydrogen by 2030 and 10 million tons per year of imports, mostly by pipeline and some as ammonia by ship. The added funding of 210 billion euros includes 28 to 38 billion euros for pipelines, 6 to 11 billion euros for storage and terminals, and 335 to 471 billion euros for new renewable electricity [3,5].

In the United States, the national targets are 10, 20, and 50 million tons per year of clean hydrogen in 2030, 2040, and 2050. Federal support includes \$ 9.5 billion for clean hydrogen and a production tax credit up to \$9.5 billion for very low-carbon hydrogen under the Inflation Reduction Act. The United States Department of Energy “Hydrogen Shot” goal is 1 dollar per kilogram [8-10].

2. Hydrogen in furnaces and commercial heaters

Furnaces and commercial heaters are essential for providing the high-temperature heat needed in industry, residential buildings, and other energy-intensive applications [11]. Traditionally, these systems rely on fossil fuels such as natural gas, but this reliance contributes significantly to global CO₂ emissions. Industry alone is responsible for nearly 20% of worldwide emissions, mainly from combustion in stationary equipment [12]. This has created growing international pressure to reduce emissions and move towards net-zero energy systems. Hydrogen is now being studied as a promising alternative fuel for furnaces and heaters. It offers the advantage of producing no direct CO₂ when burned, but its combustion behavior is very different from natural gas. Hydrogen has a wider flammability range, higher flame speeds, and higher flame temperatures, which can improve stability but also increase safety risks such as flashback and higher NO_x emissions. Studies have shown that diluting the oxygen in the oxidant stream can lower peak flame temperature and suppress NO_x formation [13-14]. However, adding hydrogen to natural gas also shortens flame length and can cause NO_x to rise quickly if not adequately controlled.

Research on industrial furnaces has confirmed both the opportunities and the challenges. For example, experiments with hydrogen-rich blends showed stable operation in mild combustion conditions, but mixtures above 50% hydrogen often required burner redesign to avoid unstable flames and excess NO_x [15]. Additives such as methane have been suggested to improve hydrogen combustion. Economic analyses of heat-treatment furnaces also indicate that while hydrogen can reduce CO₂ by more than 50%, this typically requires blends above 80% hydrogen, which increases fuel costs significantly. Tests demonstrated that hydrogen could be blended up to 45% by volume with methane while keeping NO_x emissions acceptable [16].

At the commercial scale, furnaces and heaters show similar behavior. In residential heaters, flashbacks were observed when hydrogen exceeded 20%, but safe operation was possible up to 45% with careful ignition on natural gas. For larger chamber furnaces, 30% hydrogen blends achieved substantial CO₂ reductions and raised efficiency from 18.8% to over 30%. Using 100% hydrogen as a fuel is the best option for reducing CO₂ emissions.

In summary, hydrogen has strong potential to decarbonize furnaces and heaters, but practical adoption will require balancing emissions reduction with safety, efficiency, and cost. Moderate blends (20–30%) appear most feasible in the near term, while higher concentrations may need redesigned burners, new operating regimes, and supportive policies to make them economically competitive.

3. Hydrogen SI engines and vehicles

Research on hydrogen spark-ignition engines has moved from early car demonstrations to heavy-duty and off-road machines, which need engines that can run at high loads for long periods [11]. Early systems before 2010 mostly used carburetors or port-fuel injections. These engines met emission rules but gave less power than gasoline engines [17]. New hydrogen engine designs use port-fuel injections, turbocharging, and cooled exhaust gas recirculation to improve efficiency, but direct injection is still needed to lower nitrogen oxides and increase power [18]. Engines equipped with low-pressure direct injections, moderate compression ratios, exhaust gas recirculation, and advanced nitrogen oxide aftertreatment achieve higher efficiency and power density than older port-fuel injection systems. Retrofit concepts reduce costs by converting existing diesel engines into hydrogen spark-ignition engines. This is done by adding spark plugs, lowering the compression ratio, and installing port-fuel injections; while turbocharging and exhaust gas recirculation are used to control knock, backfire, and nitrogen oxides during fast load changes [19].

Direct injection is essential because it increases air intake, improve efficiency, and avoids the backfire problem of port-fuel injections. Exhaust gas recirculation helps reduce nitrogen oxides and engines knock at high load, but it requires strong boosting and careful water handling because hydrogen combustion produces more water. New direct injection systems working at pressures of 20 to 40 bar use outward-opening injectors that give better sealing and spray control. This creates a more even air–fuel mixture and can cut nitrogen oxides emissions by about half. Challenges remain, such as measuring air–fuel ratio correctly with hydrogen slip, oil changes due to hydrogen blowby, and condensation in water-rich exhaust gas recirculation [20].

Hydrogen spark-ignition engines are most suitable for long-haul trucks and non-road machines such as construction equipment. These machines require high, steady loads, operate in harsh environments, and have limited access to charging stations, making hydrogen engines more practical than fuel cells. At high load, hydrogen engines can reach similar efficiency to fuel cells, while also having simpler cooling and proven durability. Studies of non-road machines show that limited space and radiator size often make fuel cells less practical. Overall, today's hydrogen spark-ignition engines use direct injection, strong boosting, cooled exhaust gas recirculation, and selective catalytic reduction with ammonia slip catalysts to reach diesel-like power and emissions. Ongoing work focuses on better mixture control, transient operation, and long-term durability.

4. Hydrogen in compression ignition (CI) engines

Hydrogen is difficult to use as a single fuel in CI engines because of its high auto-ignition temperature. Most research uses dual-fuel strategies, where a small pilot injection of diesel or biodiesel triggers ignition and stabilizes combustion [11]. When the hydrogen share is increased, knock, pre-ignition, and backfire become major concerns because hydrogen has wide flammability limits, very low ignition energy, and high flame speed [21]. These risks are further aggravated by a higher compression ratio, higher intake temperature, and increased boosting pressure. The compression ratio is central to the performance-emissions trade-off. Higher compression ratios improve efficiency and lower carbon emissions but also raise the risk of knocking at higher hydrogen shares. Lower compression ratios widen the safe hydrogen substitution window, but lower efficiency unless supported by injection optimization.

Injection strategy is crucial: port injection is more straightforward but less efficient and prone to backfire, while direct hydrogen injection restores power but challenges injector durability [22]. Dilution techniques are critical to suppress high temperatures and NO_x emissions. Exhaust gas recirculation (EGR) reduces in-cylinder temperature and enables higher hydrogen fractions. Inert gas dilution, particularly nitrogen, also increases knock resistance and reduces NO_x, though excessive dilution risks incomplete combustion. Water injections effectively reduce knock and NO_x while improving efficiency but must be optimized. On emissions, the benefits are clear: CO₂, CO, smoke, and unburned hydrocarbons are reduced significantly as the hydrogen share increases. The main drawback is higher NO_x formation due to faster flame speed and higher temperatures, but this can be mitigated by EGR, water injection, or optimized injection phasing [23–25].

Biodiesel pilots maintain most benefits of diesel ignition, with the added advantage of reducing lifecycle carbon. Studies show that hydrogen-biodiesel combustion achieves efficiency and reduces smoke, though NO_x often increases unless controlled [11]. The knock-free hydrogen limit can be slightly lower than fossil diesel, but careful use of EGR and dilution can extend stable operation.

5. Hydrogen in gas turbines

The move to gas turbines that burn only hydrogen presents significant opportunities for clean power, but it also brings major challenges [11]. Hydrogen flames behave very differently from hydrocarbon flames. Because hydrogen has a very high flame speed, there is a substantial risk of flashback, where the flame can move backward into the injector and damage the turbine. This makes flame stabilization one of the main design problems [26]. To keep nitrogen oxide emissions low, turbines must run with lean mixtures, but lean hydrogen flames are unstable and can suffer from thermoacoustic

oscillations or blow-off. Hydrogen also mixes very easily with air and has a wide flammability range. If the mixing is uneven, local hot spots at near-stoichiometric conditions form, and this increases nitrogen oxide production. In addition, hydrogen shows strong differential diffusion effects and thermal diffusive instabilities, which change flame shape, heat release, and how turbulence interacts with the flame. Current computer models for combustion are improving, but they still have difficulty predicting these small-scale effects at the high pressures found in turbines. The primary combustion challenges for hydrogen gas turbines are therefore to hold the flame in a stable position, prevent flashback, control oscillations, and reduce nitrogen oxides using advanced methods of injection, mixing, and cooling [27-29].

6. Progress of hydrogen integration in gas turbines: industry strategies and practical demonstrations

Gas turbines are gradually becoming more compatible with hydrogen. Major manufacturers are modifying existing designs and adding new technologies to handle more hydrogen [30]. General Electric has developed combustor systems that operate with varying amounts of hydrogen. These systems include traditional premixed designs for low hydrogen use and single-nozzle and multi-nozzle quiet combustors for higher hydrogen concentrations. These systems have already been used in refineries, steel mills, and power plants. They demonstrate that turbines can operate with over 50%

hydrogen when properly sealed, with flame detection in place, and with modified fuel systems. Field projects demonstrate that mixing hydrogen with natural gas is feasible; however, when hydrogen levels are high, it is crucial to monitor flashback control, combining quality, and stable combustion closely.

Mitsubishi Heavy Industries is making progress with its J series combined-cycle turbines, which have successfully demonstrated hydrogen co-firing and are being prepared for full-hydrogen service in the future. The company has come up with designs like multi-cluster and multi-nozzle combustors to improve mixing, stop flashback, and lower nitrogen oxide emissions. They also use high-temperature coatings and advanced cooling to keep the turbines working well at temperatures above 1600 degrees Celsius. Mitsubishi is exploring cracking ammonia as a method to utilize existing fuel transport systems for large-scale hydrogen delivery. These changes show that partial hydrogen operation is already possible. Full hydrogen capability will depend on increasing production, improving electrolysis or reforming with carbon capture, and making sure that it can be safely and reliably integrated into power plants.

7. Hydrogen as energy storage in hybrid solar - CHP microgrids

In hybrid solar-CHP microgrids (Figure 1), instances often arise where too much renewable energy is generated, such as when solar output exceeds immediate electrical and cooling needs.

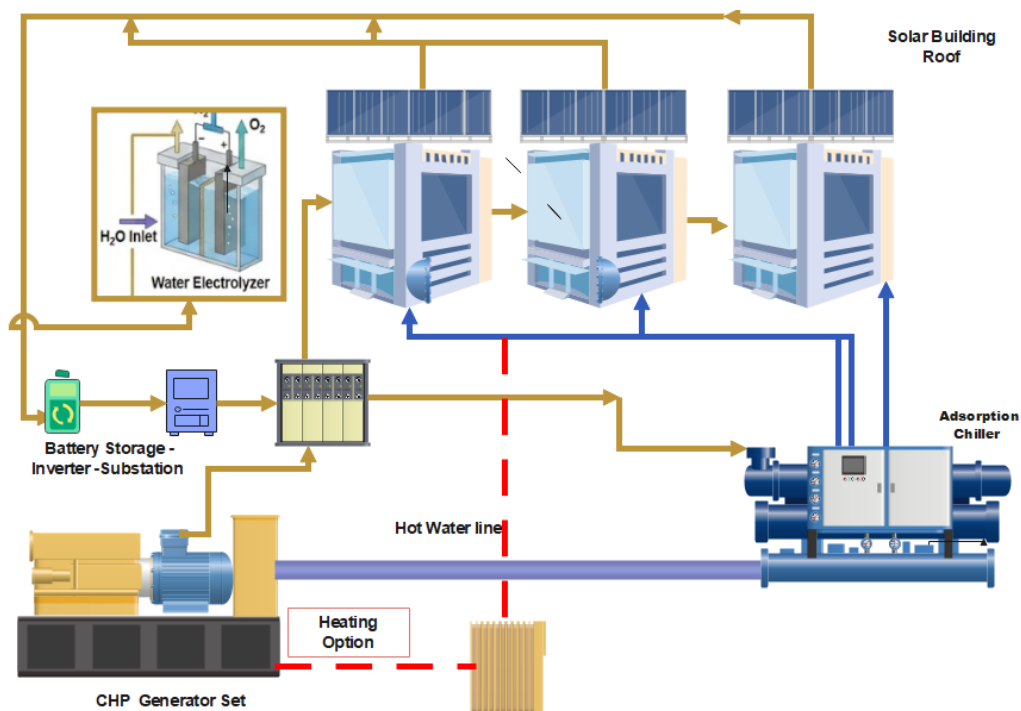


Fig. 1 Schematic of a hybrid solar-CHP microgrid with battery storage, hydrogen generation for power storage, heating option, and adsorption chiller integration [31]

Instead of cutting back on this extra power, it can be sent to electrolysis systems to make hydrogen, which is a clean and storable way to store energy. When there isn't enough sunlight or there is a lot of demand, the stored hydrogen can be used in CHP engines to make sure that electricity and heat are always available [31]. This integration gives the system a balanced and flexible way to work, turning the variability of renewable energy into an advantage by turning extra energy into a stable, long-term resource for microgrid performance that lasts.

8. Hydrogen CHP with land-optimized microgrids and hydrogen on situ production and storage

The present study emphasizes hydrogen utilization in engines and turbines; however, it is essential to

acknowledge the research on microgrid optimization [32]. Renewable microgrids (Figure 2) that are optimized for land use make it possible to produce green hydrogen on site, store it as an energy carrier, and then turn it back into power and heat using CHP. This "Renewables–H₂–CHP" trio is instrumental when land is limited and grids are weak. The microgrid takes up less space, hydrogen stores extra energy generated for a longer time than batteries, and CHP provides reliable, dispatchable energy with high overall efficiency. All these parts work together to create a small, flexible solution that enhances resilience and accelerates the use of clean hydrogen in engines and turbines.

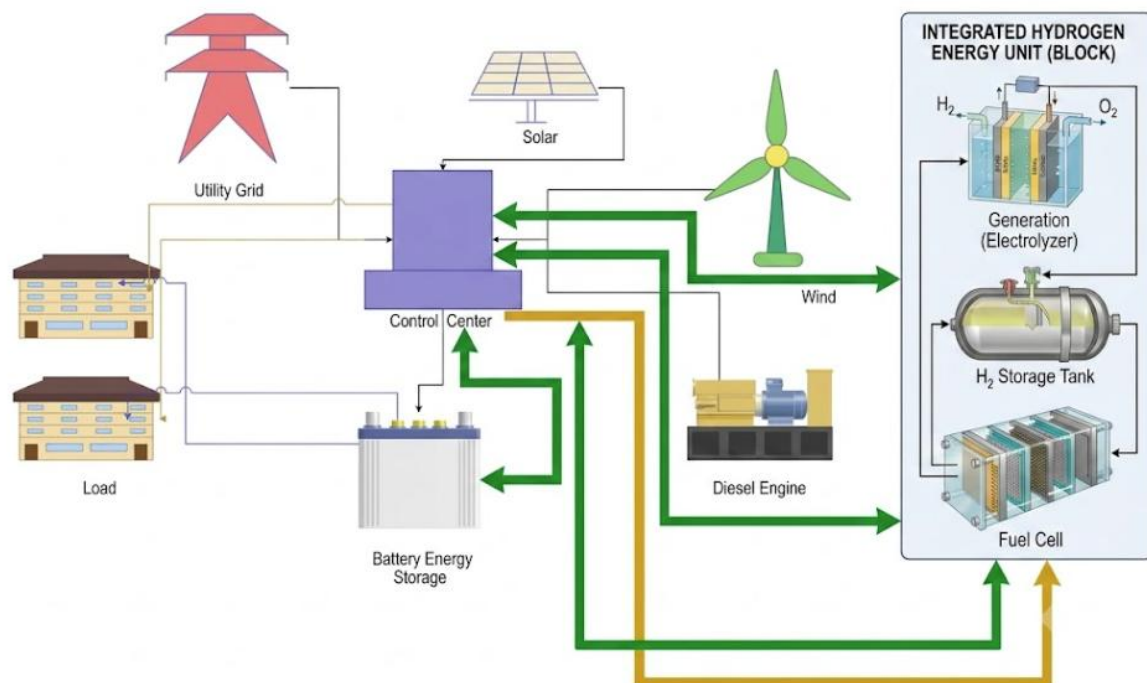


Fig 2 Hybrid solar, wind, and diesel microgrid that can store energy as hydrogen [32]

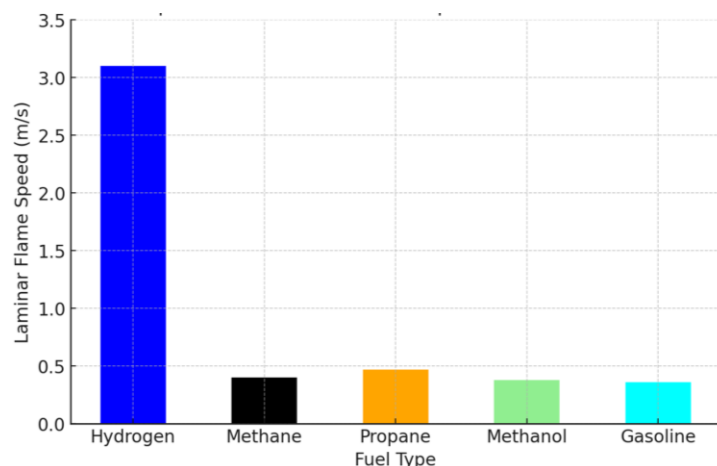
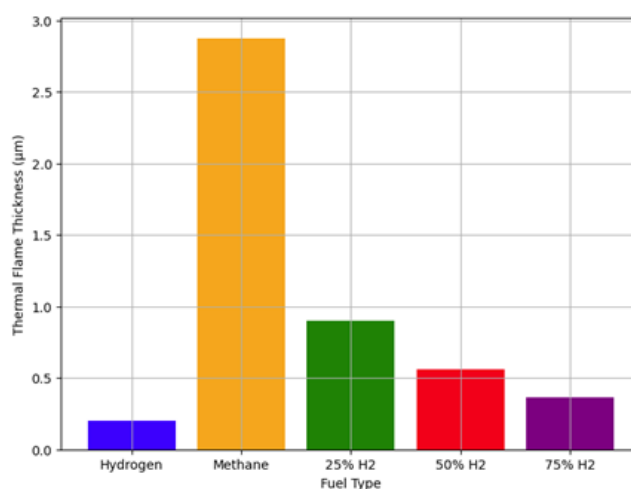
9. Hydrogen combustion kinetics and properties

To burn hydrogen, you need two parts of hydrogen and one part oxygen. This means that the air-fuel ratio is approximately 34 to 1, and the volume ratio is about 2.4 to 1 (Table 1). The compression process raises the temperature of the mixture, which must be controlled to prevent autoignition in spark-ignition engines and to start ignition in compression-ignition engines. The compression ratio and the specific heat ratio both affect thermal efficiency. Hydrogen has a higher ratio, which makes it more efficient. It doesn't take much energy to start hydrogen combustion, making it easy to light, but it's sensitive to pre-ignition. It reacts quickly because it

doesn't need much energy to start, which makes the flame speed high (Figure 3). Hydrogen flames get very hot, which makes nitrogen oxides go up, and the temperature at which they ignite is relatively low. The Lewis number for hydrogen is less than one, indicating it diffuses faster than heat. This produces thin and unstable flames (Figure 4). Hydrogen flames spread quickly. Laminar flames are uniform, but turbulent flames are more common in practice. This makes the process more efficient but also causes more pressure changes. A high flame speed can cause flashback into the intake or backfire before the valve closes. This means that the mixture, timing, and injection must be very carefully controlled.

Tab 1 Hydrogen, methane, and iso-octane properties at 293.15 K and 1 atm

Property	Hydrogen	Methane	Isooctane
Lower heating value (MJ/kg)	120	50	44.3
Higher heating value (MJ/kg)	142	55.5	47.8
Lower heating value (MJ/Nm ³)	10	33	30,656
Higher heating value (MJ/Nm ³)	12	37	33,078
Molecular weight (g/mol)	2.016	16.043	114.236
Density (kg/m ³)	0.08	0.67	692
Ratio of specific heats	1.405	1.304	1.047
Flammability limits in air (vol%)	4–75	5–15	1.1–6
Flammability limits (λ)	10–0.14	2–0.6	1.51–0.26
Flammability limits (ϕ)	0.1–7.1	0.5–1.67	0.66–3.85
Stoichiometric air-to-fuel ratio (kg/kg)	34.2	17.1	15
Stoichiometric air-to-fuel ratio (kmol/kmol)	2.39	9.55	59.67
Minimum ignition energy (mJ)	0.02	0.28	0.28
Minimum quenching distance (mm)	0.64	2.03	3.5

**Fig 3** Comparison of laminar flame speeds of hydrogen and conventional hydrocarbon fuels [33]**Fig 4** Thermal flame thickness of hydrogen, methane, and hydrogen–methane blends comparison across pure fuels and mixtures (25%, 50%, and 75% hydrogen by volume) demonstrating hydrogen's thinner flame structure

10. Comparative analysis of hydrogen combustion profiles and flame characteristics using different mechanisms

When modeling hydrogen combustion, the two chemical mechanisms GRI-Mech 3.0 and H_2 - O_2 give nearly the same result. Both show that the temperature of the flame rises quickly as the flame front grows, then levels off at about 2,300 Kelvin. This means that they both demonstrate the same process of heat release and reaction. Figure 5 shows this by showing that the temperature profiles from both mechanisms are almost the same. Figure 6 combines the sensitivity analysis into one chart. It shows how different chemical reactions speed up or slow down the flame. The H_2 - O_2 mechanism is more sensitive to reactions that involve hydrogen itself.

The GRI-Mech 3.0 mechanism, on the other hand, includes more reactions that are important when different fuels are present. Figure 7 shows how methane burns. Its laminar flame speed reaches a peak when the air-fuel ratio is balanced, and then it drops when the mixture gets too lean or too rich. Figure 8, on the other hand, shows that hydrogen burns with a much higher laminar flame speed under the same conditions. This proves that hydrogen is much more reactive. Figure 9 shows the main parts of the hydrogen flame. As the flame burns, hydrogen decreases, oxygen is used up, and water increases. Finally, Figure 10 shows the heat release rate and the temperature profile in a premixed hydrogen flame. There is a sharp spike in heat release near the start of combustion, and then the temperature stays stable at a high level once the flame is fully developed.

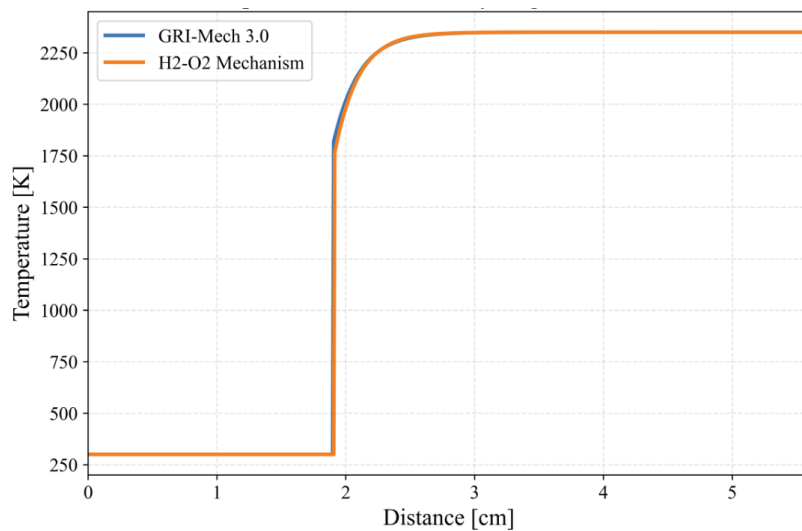


Fig 5 Temperature profiles for hydrogen combustion using GRI-Mech 3.0 and H_2 - O_2 mechanisms [34,35]

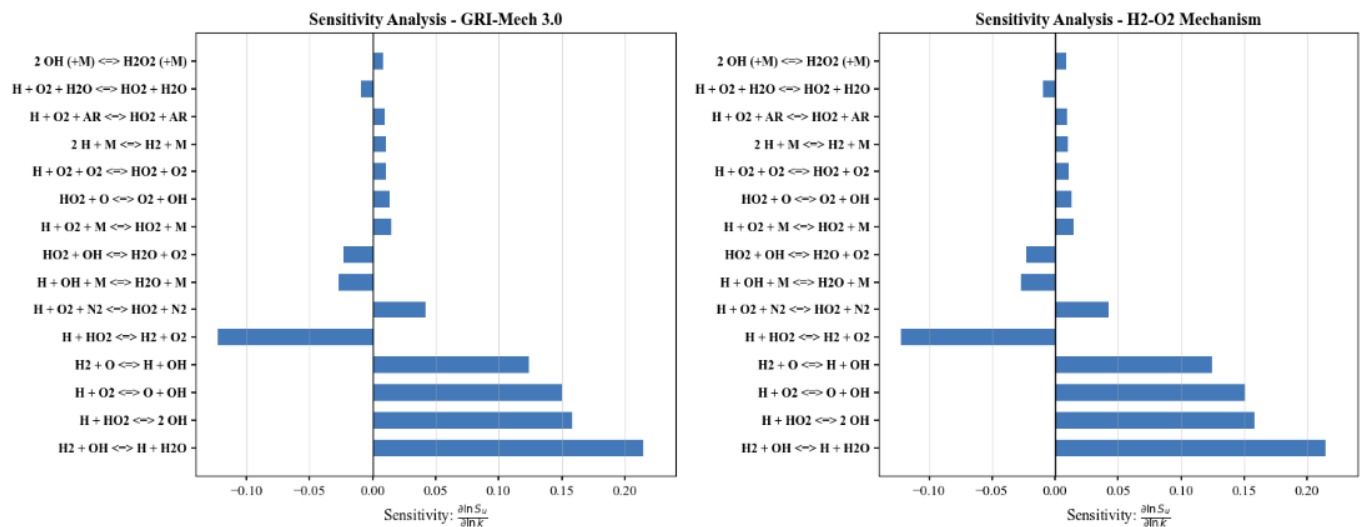


Fig 6 Sensitivity analysis of hydrogen combustion reactions for GRI-Mech 3.0 and H_2 - O_2 mechanisms [34,35]

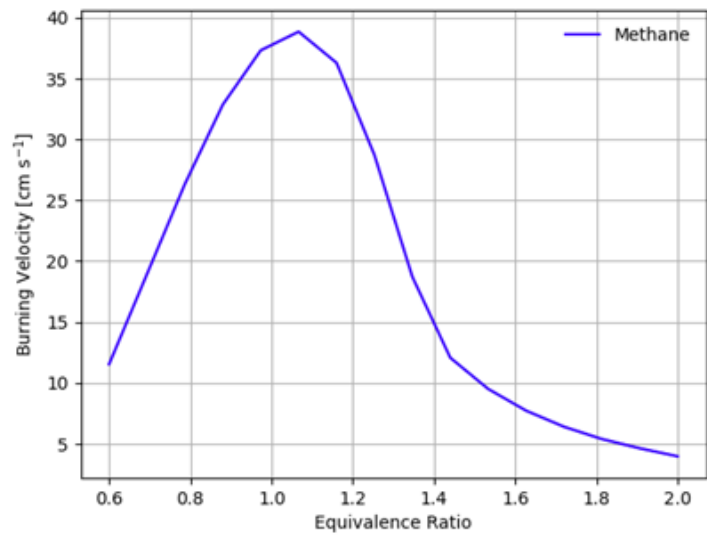


Fig 7 Laminar Flame Speed Characteristics for Methane Across Equivalence Ratios [34,35]

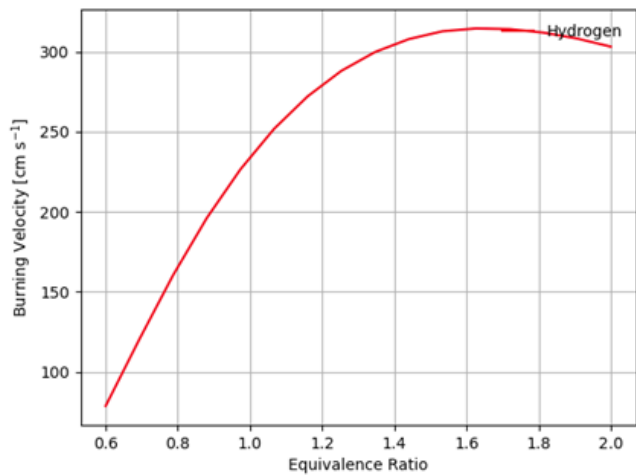


Fig 8 Laminar flame speed characteristics for hydrogen across equivalence ratios [34,35]

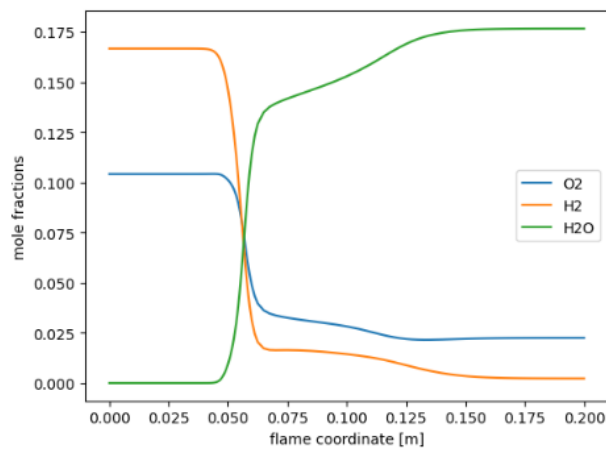


Fig 9 Major species profiles during hydrogen combustion in a premixed counterflow flame [34,35]

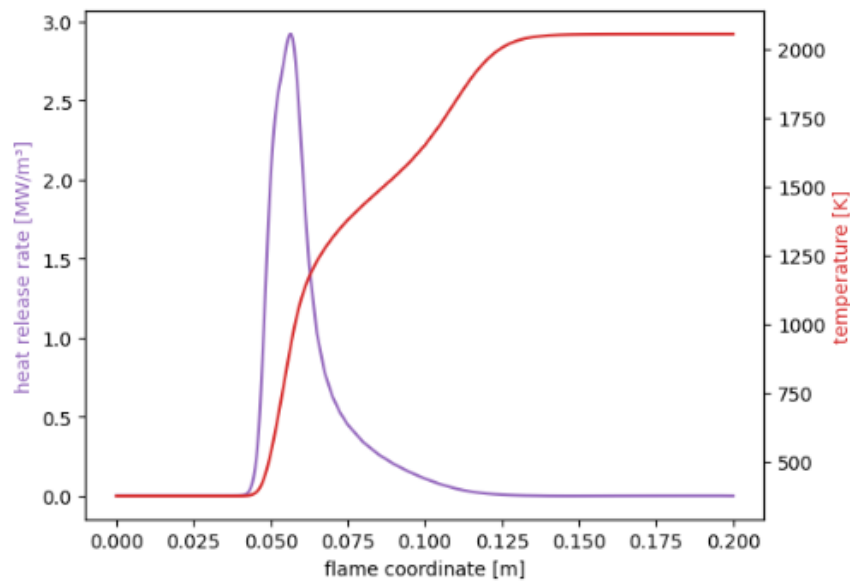


Fig 10 Heat release rate and temperature profiles across a premixed hydrogen counterflow flame [34,35]

11. Limitations and future work

The present work is intentionally focused on hydrogen combustion characteristics, combustion kinetics, flame behavior, and engineering applications in internal combustion engines, industrial furnaces, commercial heating systems, and gas turbines. Consequently, topics such as hydrogen production pathways, production economics, storage technologies, transportation infrastructure, carbon capture regulations, and hydrogen embrittlement are discussed only briefly where necessary to provide engineering context. A comprehensive treatment of these subjects would considerably broaden the scope of the manuscript and is therefore beyond the objective of this review.

Future work should provide dedicated reviews addressing hydrogen production technologies, including steam methane reforming (SMR), water electrolysis (alkaline, PEM, and SOEC), biomass conversion, natural (white) hydrogen extraction, hydrogen storage systems, production costs, and the evolving regulatory frameworks governing low-carbon hydrogen. In addition, future reviews should investigate hydrogen embrittlement, material degradation, component lifetime, sealing technologies, and structural integrity under long-term hydrogen exposure, as these remain critical challenges for large-scale hydrogen deployment. Together with the combustion studies presented in this review, these complementary topics will provide a comprehensive understanding of the hydrogen value chain from production through end-use combustion applications.

12. Conclusions

Hydrogen is a very flexible energy carrier that can help decarbonize deeply in areas where electrification alone isn't enough. It can be made in many ways, from low-cost but carbon-intensive grey hydrogen to fully

renewable green and nuclear-based pink hydrogen. This makes it a good starting point for future clean energy markets. Green hydrogen is still more expensive than other types of hydrogen, but the prices of electrolyzers and renewable electricity are dropping quickly, which shows that the U.S. and EU are making good progress toward their goals of about 1 USD/kg hydrogen. Integrating hydrogen into global energy systems will require major infrastructure improvements, such as building dedicated hydrogen pipelines, ammonia shipping routes, and industrial storage. Hydrogen's physical and chemical properties change the way engineers think about problems in combustion applications. Its low ignition energy, high flame speed, and wide flammability range make combustion more responsive, but they also make flashback, backfire, and NO_x formation more likely. Moderate hydrogen blends (20–40%) can help reduce CO_2 emissions in the in furnaces and commercial heaters. Higher blends, on the other hand, need new burners, precise mixing strategies, and new control systems. The non-road equipment the Hydrogen engines prove superiority [36] and Hydrogen SI engines are making quick progress, especially with direct injection, high boosting, cooled EGR, and new aftertreatment systems that can give diesel-like performance. Hydrogen dual-fuel CI engines have much lower carbon emissions, but it is still important to control knock and NO_x . Gas turbines are among the most promising high-efficiency applications for hydrogen; however, hydrogen combustion in gas turbines remains technically challenging. OEM demonstrations illustrate that partial hydrogen co-firing is already feasible in many industrial settings. To move toward 100% hydrogen operation, we will need new combustor designs that keep lean flames stable while stopping thermoacoustic instabilities, flashback, and localized hot spots. Hydrogen makes microgrids much more flexible and resilient at the system level. Hydrogen allows for long-

term energy storage, efficient heat recovery, and on-site fuel production when used with solar PV, wind and CHP engines. This cuts down on land use and reliance on the grid. This setup allows for a lot of renewable energy use without hurting reliability or meeting thermal demand. In general, hydrogen is a strong way to get rid of carbon in industrial heating, transportation, power generation, and distributed energy systems. However, for large-scale deployment to happen, there needs to be coordinated progress in safety, materials, system integration, combustion technology, and economic policy. Future research should concentrate on high-pressure combustion kinetics, transient behavior in real engines, flame stabilization at the turbine scale, techno-economic optimization of hydrogen microgrids, and the long-term durability of hydrogen components. Hydrogen can turn heavy industry, transportation, and power systems into truly low-carbon infrastructures if innovation continues.

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